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Snow cover sensitivity to black carbon deposition in the Himalaya: from ice core measurements to regional climate simulations

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Context

Black Carbon is one of the main anthropogenic compound affecting the climate system: Bond et al. (2013) suggest the total climate forcing of black carbon through all forcing mechanisms to reach +1.1 W m^{-2}, with a quite elevated uncertainty of 90% (bounds of +0.17 to +2.1 W m^{-2}). This estimation refers to both direct and indirect atmospheric effects, but also to the impact of BC on snow albedo. Anthropogenic BC currently deposited on snow reduces the snow cover duration from several days in the Northern Hemisphere (Ménégoz et al., 2013). Such forcing contributes to the significant decrease of the snow cover extent observed during the last decades and expected for the next century (Brutel-Vuilmet et al., 2007). The Himalayan region host extended glaciers and is snow-covered during a large part of the year. Its atmosphere is strongly affected by BC anthropogenic emissions, taking place both in the Indian plain and in the crowded mountainous areas. Consequently, atmospheric BC concentration reaches very high rates in this region (Ramanathan *et al.*, 2007), even at elevated areas (Bonasoni *et al.*, 2008). Here, we use a global climate model with a stretched grid, to reach a fine resolution over the Himalaya, in order to quantify the effect of BC deposition on the snow cover duration. The temporal variation and the order of magnitude of the aerosol concentration in the snow are confronted to an ice core record performed in a Nepalese glacier. Finally, we estimate the surface radiation and the temperature change associated with the BC deposition on the Himalayan snow.

Aerosol deposition: from ice core measurements to large scale simulations

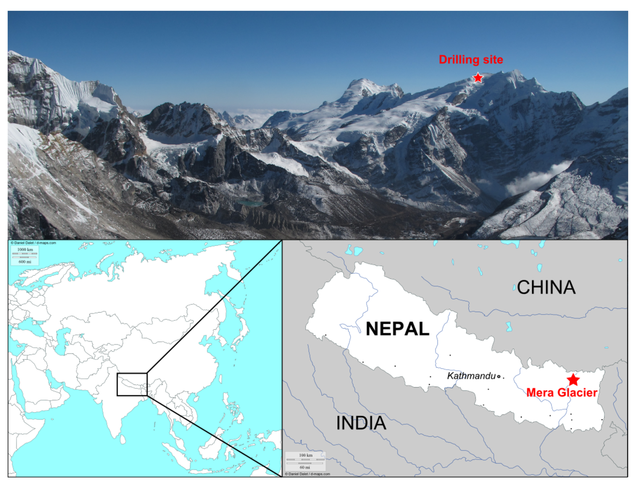

Fig. n°1 : Location of the Ice core site (Mera Peak, 6476m a.s.l., N27°43', E86°52',Nepal)

Table 1 : BC and dust concentration in the snow, BC and dust deposition, and snow fall. Observation: N27°43', E86°52', 6478 m a.s.l.; Model: N28°00', E86°52', 5552 m a.s.l.

	Observation (black) - model (red)		
	Annual	Inter-monsoon	Monsoon
BC concentration (μ.kg^{-1})	3 - 201	9.25 - 285	1.06 - 27
Dust concentration (mg.kg^{-1})	10.1 - 10.4	11.1 - 13	10.1 - 5
Dust deposition (g.m^{-2}.yr^{-1})	10 - 6.4	28% - 60%	72% - 40%
BC deposition (mg.m^{-2}.yr^{-1})	3.2 - 52	75% - 59%	25% - 41%
Snowfall (mm w.eq. month^{-1})	94 - 83	33 - 42	61 - 175

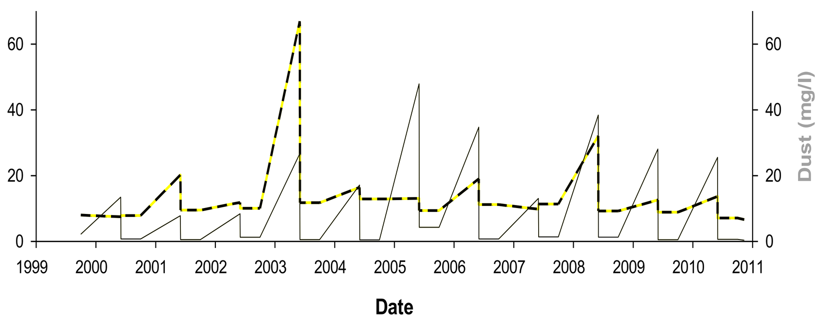

Fig. n° 2: Measured snow surface concentration of BC and dust (N27°43', E86°52', 6478 m a.s.l.)

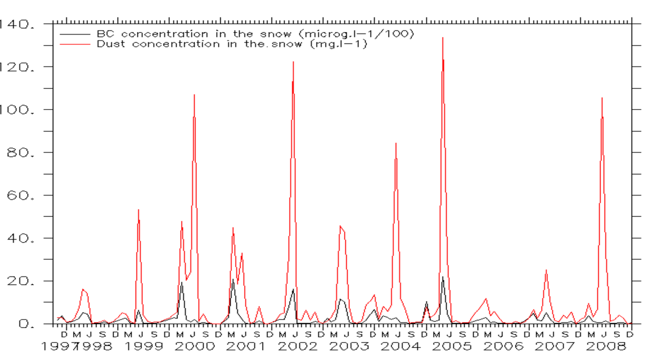

Fig n°3 : Modelled snow surface concentration of BC and dust *(*N28°00', E86°52', 5552 m a.s.l.)

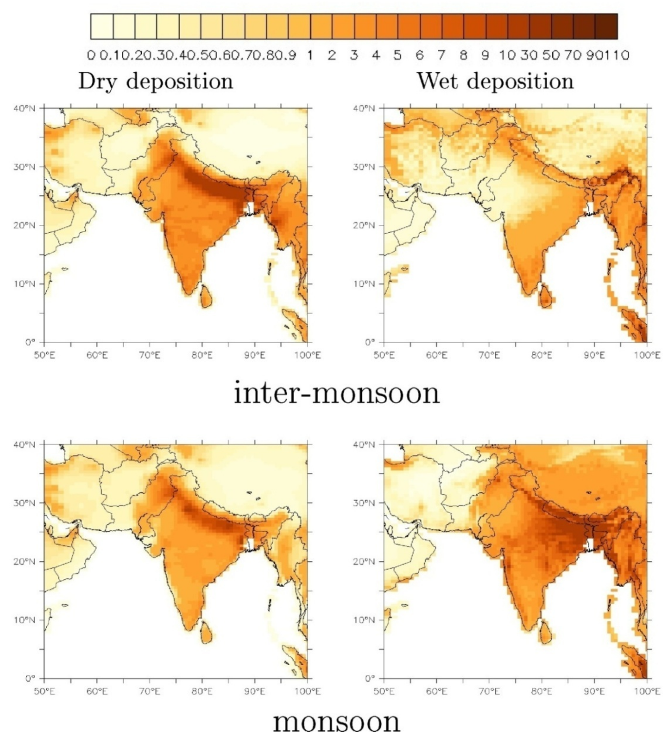

Fig n°4 : BC deposition modelled over 1998-2008 (mg.m^{-2}.month.$^{-1}$)

An ice core was extracted from the Mera glacier (6476m a.s.l., N27°43', E86°52',Nepal) to reconstruct the aerosol fluxes in this region over the period 2000-2010. BC shows a strong seasonal deposition cycle in the snow, with a maximum during pre-monsoon season (Fig. 2). Dust deposition is more constant over the year. The BC content in the snow ranges from 10 to 50 μg.l^{-1}, whereas dust concentration reaches thousand times higher levels. Due to the coarse resolution of our climate model, we cannot compare directly the observed and the modeled aerosol concentration in snow. The grid cell located over the Mera Peak has a too low elevation, and is therefore to warm to allow snowfall. 50 km more on the North (in the Mt Everest area), the grid cell surface height reaches 5552 m, which allows to simulate a seasonal snow cover. Here, the seasonal variations of BC and dust in the snow shows some similarities with the ice core observation (Fig. 2, Fig. 3, Table 1). Dust concentration reaches levels comparable to those observed in the ice of the Mera Peak. It is not the case for BC concentration which reaches concentrations 10 to 100 times larger in the model in comparison with the ice core observation (Fig. 3, Fig. 7a and Table 1). Such difference is mainly related to the altitude differences between the ice core site (6476 m) and the model grid cell (5552 m). Recently, Kaspari et al. (2014) measured BC concentration in snow sampled at the Mera La (5400 m) reaching an average of 180 μg.l^{-1}. Therefore, we estimate that our model is more representative of the surface processes occurring at intermediate elevations (~5500 m) than at high elevation (>6000 m). Our simulations suggest that dry deposition brings particularly strong amount of BC at the southern slopes of the Himalaya, mainly during the pre-monsoon period, whereas wet deposition brings lower but significant level of BC in regions located farther on the North (Fig. 4).

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Performing experiments with the aerosol – climate model LMDZ-INCA

Table 2: 4 sensitivity experiments performed with LMDZ-INCA

Simulation	Resolution	Snow albedo
SG1	96x95x19	With BC deposition
SG2	96x95x19	Without BC deposition
SZ1	144x142x19 Zoom	With BC deposition
SZ2	144x142x19 Zoom	Without BC deposition

We performed 4 simulations with the global climate model LMDZ (Hourdin et al., 2006), coupled with the aerosol module INCA. Two simulations were run with a standard coarse-gridded resolution (96x95) whereas the two others were based on a 143x144 stretched grid, with a zoom on the Himalaya (See Fig. 5). For each resolution, we performed two simulations with a detailed snow albedo scheme (Wiscombe and Warren, 1980): One using the BC deposition computed from the INCA model aerosol, and another without BC in the snow (see Table 2). The difference between these simulations is used to quantify the climate effects of BC on snow.

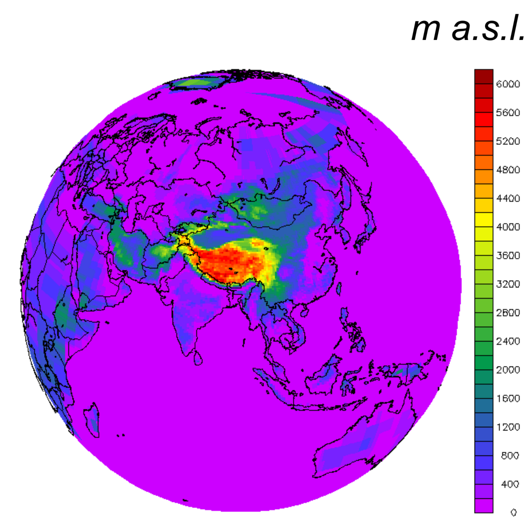

Fig n°5 : Surface altitude in the stretched grid of LMDZ, with a zoom over the Himalaya (144x143 points with a ~50 km resolution over the Himalaya)

Snow cover duration estimated from satellite and models

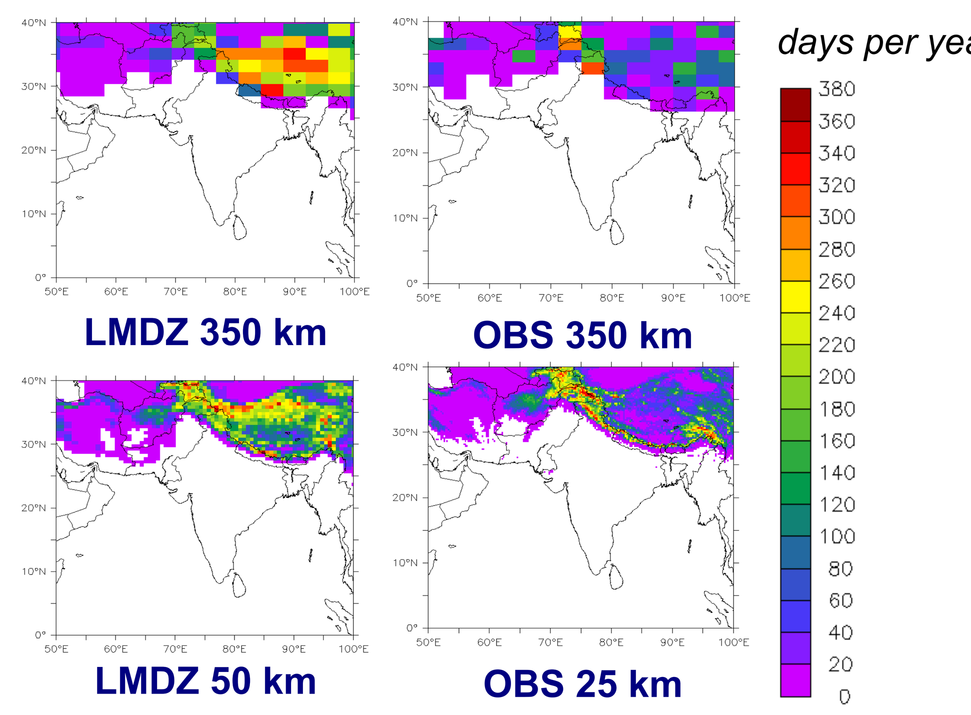

Fig. n°6: Snow cover duration (days per year) averaged over 1998-2008. LMDZ simulations were performed with the BC effect on snow albedo. IMS satellite observations were provided by NSIDC.

A fine resolution is essential to simulate the snow cover duration.

Impact of aerosol deposition on the snow cover duration and energy balance

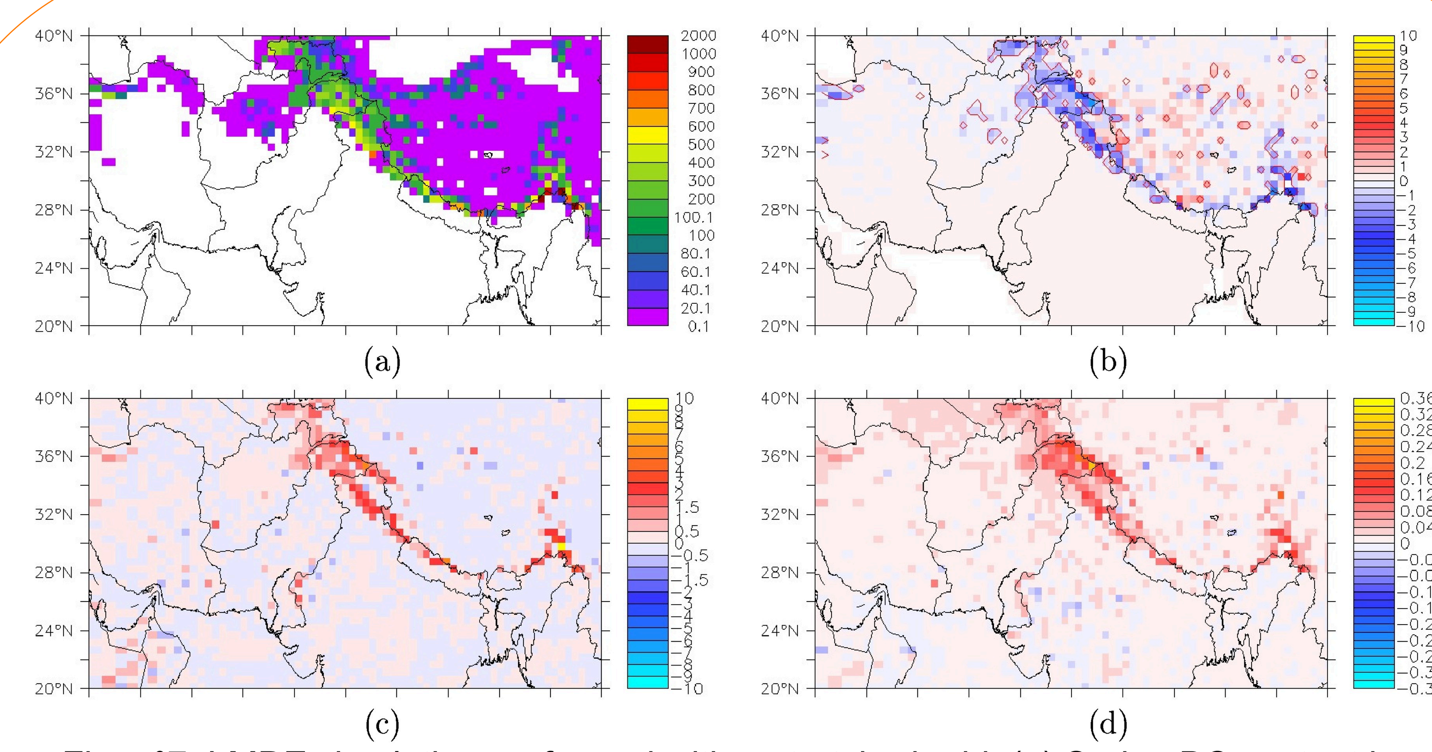

Fig. n°7: LMDZ simulation performed with a stretched grid: (a) Spring BC content in the snow (µg.kg^{-1}). (b) Difference of snow cover duration (days per year) between 2 simulations performed with and without the snow albedo variations induced by BC deposition. Areas with statistically significant differences, according to a two-sample t test, are red-contoured. (c) Same difference but for annual mean of solar radiation (W.m^{-2}). (d) Same difference but for annual mean temperature (°C).

Our simulation indicate that anthropogenic aerosol emissions bring large amounts of pollutants in the Himalayan snow. The BC content in the surface snow reach its maximum value during the spring, with values ranging between 10 and 500 µg.kg^{-1} (Fig. 7a). This BC deposition induces a reduction of the snow cover duration of 1 to 8 days per year over large areas of the Western Himalayas and the Karakorum (Fig. 7b). The snow cover is largely less extended in the Tibetan plateau, in Central and Eastern Himalaya, where the BC forcing is therefore less visible. Such forcing can not be estimated with coarse gridded climate models, who generally overestimate both snow cover and BC forcing in these regions. BC deposition on snow induce an increase of solar radiation at the surface which reaches an annual mean of 1 to 3 W.m^{-2} in the high altitude areas of the Himalaya (Fig. 7c). Two main processes explain such forcing: (1) the reduction of the snow albedo induced by BC deposition. (2) the decrease of the snow cover duration, increasing a strong increase of the surface albedo when the soil is free of snow. Finally, we simulate the present-day BC deposition on snow to increase the 2 meters air temperature from 0.05 to 0.3°C over large areas of the Himalaya.

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